

# Neutrino oscillometry

**J.D.Vergados<sup>1</sup>, Y. Giomataris<sup>2</sup> and Yu. N. Novikov<sup>3</sup>**

<sup>1</sup> Physics Department, University of Ioannina, Ioannina, Greece

E-mail: [vergados@uoii.gr](mailto:vergados@uoii.gr)

<sup>2</sup> CEA, Saclay, DAPNIA, Gif-sur-Yvette, Cedex, France

<sup>3</sup> Petersburg Nuclear Physics Institute, 188300, Gatchina, Russia

**Abstract.** Neutrino oscillations are studied employing sources of low energy monoenergetic neutrinos following electron capture by the nucleus and measuring electron recoils. Since the neutrino energy is very low the oscillation length  $L_{23}$  appearing in this electronic neutrino disappearance experiment can be so small that the full oscillation can take place inside the detector so that one may determine very accurately the neutrino oscillation parameters. In particular, since the oscillation probability is proportional to  $\sin^2 2\theta_{13}$ , one can measure or set a better limit on the unknown parameter  $\theta_{13}$ . One, however, has to pay the price that the expected counting rates are very small. Thus one needs a very intensive neutrino source and a large detector with as low as possible energy threshold and high energy and position resolution. Both spherical gaseous and cylindrical liquid detectors are studied. Different source candidates are considered

## 1. Introduction.

The discovery of neutrino oscillations can be considered as one of the greatest triumphs of modern physics. It began with atmospheric neutrino oscillations [1] interpreted as  $\nu_\mu \rightarrow \nu_\tau$  oscillations, as well as  $\nu_e$  disappearance in solar neutrinos [2]. These results have been recently confirmed by the KamLAND experiment [3], which exhibits evidence for reactor antineutrino disappearance. As a result of these experiments we have a pretty good idea of the neutrino mixing matrix and the two independent quantities  $\Delta m^2$ , e.g.  $|m_2^2 - m_1^2|$  and  $|m_3^2 - m_2^2|$ . Fortunately these two  $\Delta m^2$  values are vastly different,

$$\Delta m_{21}^2 = |m_2^2 - m_1^2| = (7.65_{-0.20}^{+0.23}) \times 10^{-5} (eV)^2, \quad \Delta m_{32}^2 = |m_3^2 - m_2^2| = (2.4_{-0.11}^{+0.12}) \times 10^{-3} (eV)^2.$$

This means that the relevant  $L/E$  parameters are very different. Thus for a given energy the experimental results can approximately be described as two generation oscillations. For an accurate description of the data, however, a three generation analysis [4],[5] is necessary.

In all of these analyses the oscillation length is much larger than the size of the detector. So one is able to see the effect, if the detector is placed in the right distance from the source.

The most precise and unambiguous way to measure neutrino oscillations would be to determine changes in the flux of the given flavor of neutrinos over the entire oscillation length. Since the oscillation length is proportional to neutrino energy, the proper neutrino oscillometry would require a detector hundreds or even thousands of kilometers long if used with the present or proposed neutrino beams! As this is unrealistic, all beam experiments aiming at neutrino oscillations consider just a single or at most two point measurements instead of the

full oscillometric approach. Also when using reactor neutrinos, the distance from the source to the first minimum is about 2 km - still beyond the current technological and financial boundaries for a detector. To be able to perform neutrino oscillometry using a realistic-size detector like LENA (100 m long) one needs a strong source of monoenergetic neutrinos with the energy of a few hundred of keV. Such a source could be produced in a nuclear reactor making neutrino oscillometry with LENA possible [6]. Neutrino oscillometry provides a competitive and considerably less expensive alternative to long baseline neutrino beams.

The best way to detect low energy electron neutrinos is by measuring electron recoils from neutrino-electron scattering. The total neutrino electron scattering cross section be cast in the form:

$$\sigma(L, x, y_{th}) = \sigma(0, x, y_{th}) (1 - \chi(x, y_{th}) p(L, x)) \quad (1)$$

with  $x = \frac{E_\nu}{m_e}$  and  $y_{th} = \frac{(T_e)_{th}}{m_e}$ , with  $(T_e)_{th}$  the threshold electron energy imposed by the detector and

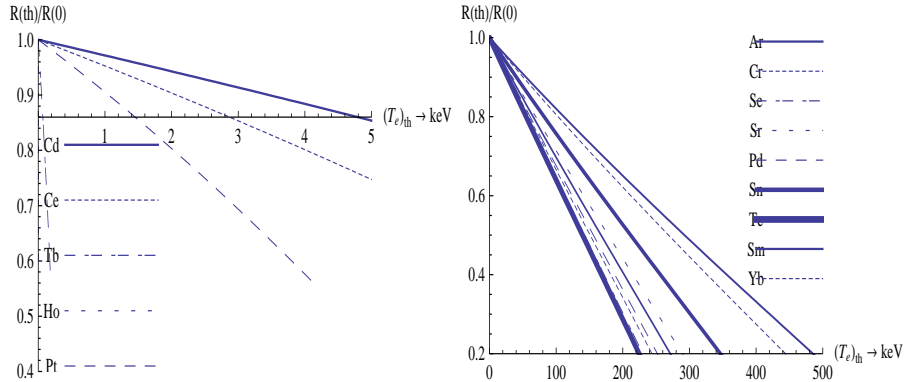
$$p(L, x) = \sin^2 \left( \frac{0.595922L}{33x} \right) \sin^2(2\theta_{solar}) + \sin^2 \left( \frac{0.595922L}{x} \right) \sin^2(2\theta_{13}) \quad (2)$$

with  $L$  the source detector distance in meters. The functions  $\sigma(0, x, y_{th})$ , the cross section in the absence of oscillation, and  $\chi(x, y_{th})$ , which takes care of the other neutrino flavors, have been previously described [6]. The oscillation length of interest to us take the form:

$$L_{32} = \frac{2.48[\text{m}] E_\nu}{\Delta m_{32}^2 [\text{eV}]^2} \Rightarrow L_{32}[\text{m}] \approx E_\nu[\text{keV}] \quad (3)$$

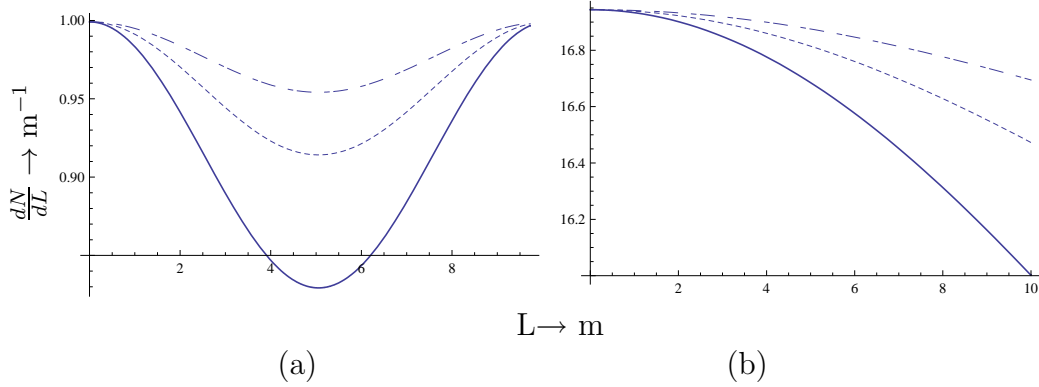
The values in the square brackets in Eqs (3) indicate the dimensions used.

The neutrino sources of interest are divided into two categories: Those which have  $L_{32} \leq 50$  m and those with  $L_{32} > 110$  m. For the former nuclides the TPC counting method can be used in the gas-filled NOSTOS sphere approach [7], [8], whereas for both and mainly for the latter category with the larger  $L_{32}$ , the long liquid scintillator (LS) detector [9] is preferable. One of the main advantages of the spherical TPC detectors is the very low energy threshold [10] they can achieve (0.1 keV), which allows them to take advantage of the very low energy neutrinos. From this point of view a comparzon between the two types of detectors is given in Fig. 1.



**Figure 1.** The dependence of the rate on the energy threshold,  $T_{th}$ , in the case of a gaseous spherical TPC detector on the left and the LENA detector on the right.

For a spherical detector two typical examples, obtained with a threshold of 0.1keV, are shown in Fig. 2. Clearly a compromise has to be made to achieve as large as possible portion of the oscillation inside the detector with a reasonable detection rate. Since the beautiful results of



**Figure 2.** The rate  $\frac{dN}{dL}$  (per meter) for Ar at 10 Atm with 1 Kg of  $^{157}\text{Tb}$  (a) and  $^{193}\text{Pt}$  (b) as a function of the source-detector distance (in m). The results shown correspond to  $\sin^2 2\theta_{13} = 0.170, 0.085$  and  $0.045$  (decreasing from bottom to top). This rate was obtained for a running period equal to the half life of the source. The analysis is much simpler than that for the cylindrical geometry since the geometric factor  $g_{av}$  for the spherical detector is unity.

the first category have been previously discussed [7], [6], in this paper we will concentrate on the second category.

## 2. Short baseline neutrino oscillations-The detection principle

Any change of scattering rate as a function of position, in excess of the geometric factor would give, for the first time, a continuous (oscillometric) measure of flavor disappearance.

The detector for  $\nu - e$  scattering events should be as long as possible and should have a large fiducial volume. It's energy registration threshold should be as low as possible since to have short oscillation length one needs low energy neutrinos. Presently only liquid scintillator (LS) technology can provide the required low detection threshold of 200 keV [11]. The proposed LENA detector would match these requirements. Moreover, with the suggested length of about 100 m LENA would be the longest LS detector ever build. Due to the improved signal processing and timing characteristics as compared to the operating LS detectors [11] the expected position sensitivity of LENA will be better than 50 cm even at the level of a few hundreds of keV of the recoil energy of the electron. The energy resolution would be  $\sim 10\%$  in this energy region [9].

As the cross-sections for  $\nu - e$  scattering are tiny, a very strong neutrino source should be used to provide adequate statistics. Fortunately, there are many nuclei decaying via electron capture (EC). Since EC is a two body process the emitted electron neutrino is monoenergetic and carries most of the transition energy. Table 1 lists some of the isotopes decaying via EC with suitable  $Q$  values to produce monoenergetic neutrinos of a few hundreds of keV and with half-lives of a few months allowing for convenient handling. They are relatively easy to produce via neutron capture reaction, see, e.g., the GALLEX experiment [12] for the 62 PBq  $^{51}\text{Cr}$  source.

The number of events in between  $L$  and  $L + dL$ , where  $L$  is the distance between the center of the source and the detection point, can be written in the following form [6]:

$$R_0 \frac{dN}{dL} = f_{\Phi} \Lambda g_{av}(u, L/R_0) \tilde{\sigma}(L, x, y_{th}), \quad (4)$$

where

$$\Lambda = \frac{G_F^2 m_e^2}{2\pi} R_0 N_{\nu} n_e \quad (5)$$

**Table 1.** Neutrino sources which could be produced by irradiation in the neutron reactors. The intensities of neutrino sources per second have been estimated per 1 kg of the target element with the natural isotope abundances and assuming a 10 day irradiation with the neutron flux of  $5 \times 10^{14}$  n/cm<sup>2</sup>/s. Neutron capture cross sections were taken from [http://ie.lbl.gov/].

Nuclide	$T_{1/2}$ , d	$Q_\epsilon$ (keV) (keV)	$E_\nu$ (keV)	$E_{e,max}$ (keV)	Ir. target (10 d)	$\nu$ -intensity (s <sup>-1</sup> ) (per kg)
<sup>37</sup> Ar	35	814	811 (100%)	617	Ar	$8.3 \times 10^{15}$
<sup>51</sup> Cr	28	753	747 (90%)	560	<sup>50</sup> Cr	$2.3 \times 10^{16}$
<sup>75</sup> Se	120	863	450 (96%)	287	Se	$1.1 \times 10^{14}$
<sup>113</sup> Sn	116	1037	617 (98%)	436	Sn	$8 \times 10^{11}$
<sup>145</sup> Sm	340	616	510 (91%)	340	Sm	$2 \times 10^{12}$
<sup>169</sup> Yb	32	910	470 (83%)	304	Yb	$1.1 \times 10^{15}$

with  $N_\nu$  the number of neutrinos emitted by the source,  $n_e$  the density of electrons in the target ( $n_e = 3 \times 10^{29}$  m<sup>-3</sup> for LENA),  $R_0$  the radius of the target and  $\tilde{\sigma}(L, x, y_{th})$  is the neutrino - electron cross section in units of  $G_F^2 m_e^2 / 2\pi$ . The quantity  $f_\Phi$  reflects the fraction of the total flux relevant for the detector ( $f_\Phi=1$ , and 1/2 for a spherical detector (with the source at the center) and a cylindrical detector (with the source at the center of one of its bases respectively). The geometric factor  $g_{av}(u, L/R_0)$  in the case of a spherical detector is unity, while for a cylindrical geometry has been previously given [6].

If one is content in extracting the value of the mixing angle only, this can be achieved by integrating the event rates over all  $L$  in the detector. This essentially involves integrating the cross section over  $L$ , folded with the function  $g_{av}(u, L/R_0)$ , i.e. integrating Eq. (4) over the  $L$ -values allowed by the detector. For sufficiently small mixing angle one can show that the event rate (in units of  $\Lambda$ ) takes the form:

$$\frac{N}{\Lambda} = -A \sin^2 2\theta_{13} + B \quad (6)$$

for <sup>51</sup>Cr  $A = 0.048304$  and  $B=0.982456$ . Then, depending on the specifics of the experiment total number of events,  $N_0$  can be presented in the form:

$$N_0 = -a \sin^2 2\theta_{13} + b \quad (7)$$

### 3. The physics case for neutrino oscillometry

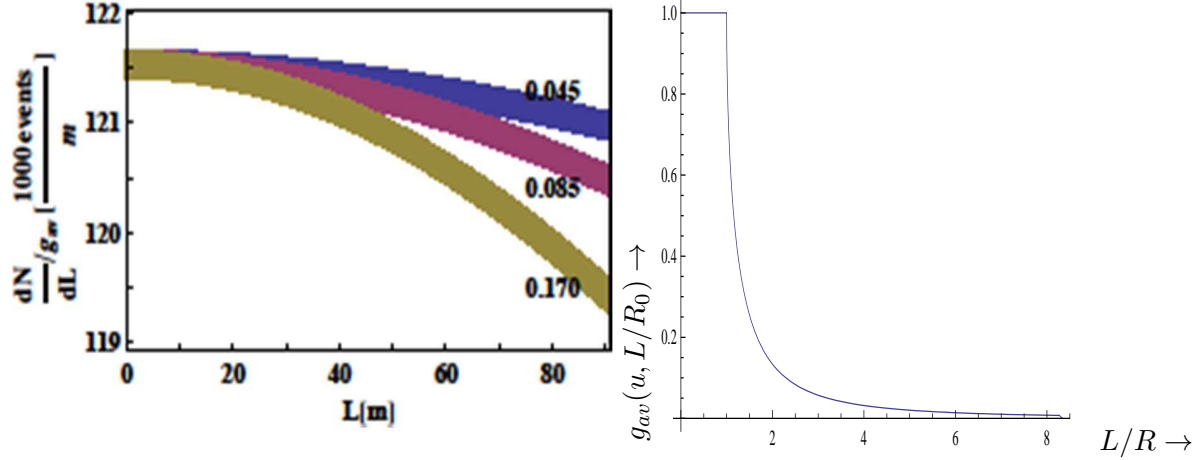
Neutrino oscillometry offers an elegant way to solve a number of questions related to neutrino oscillations: a precise determination of the mixing angle  $\theta_{13}$  and the oscillation length  $L_{23}$ , confirmation of the results of the “global” analysis of the oscillation data, and determination of the neutrino mass hierarchy. The latter would require a simultaneous long baseline measurement with the same detector.

#### 3.1. Determination of the mixing angle $\theta_{13}$

The big advantage of the short baseline oscillometry is that there is no matter influence in the observed events. As it is well known [5],[13] this matter effect gives degeneracy in the determination of the oscillation parameters in the long baseline experiments and should also be taken into consideration in some oscillation experiments with the reactor antineutrinos.

The angle  $\theta_{13}$  can be determined from the analysis of both differential number of  $\nu - e$  scattering events related to the length  $dL$  and the total number of events  $N_0$  collected during

the time of data acquisition in the full volume of LENA-detector. Differential curves for the neutrino scattering from the source  $^{51}\text{Cr}$  are shown in Fig. 3. As can be seen from this figure, the curves for different mixing angles  $\sin^2 2\theta_{13}$  are well separated within the length of LENA detector.



**Figure 3.** The number of the  $\nu - e$  scattering events over the length  $dL$  divided by the geometric factor  $g_{av}$ . The calculated values correspond to 5 data acquisition cycles, 55 days each with the  $^{51}\text{Cr}$  source installed at the top of LENA tank. The bottom (green), the middle (red) and the top (blue) correspond to  $\sin^2 2\theta_{13} = 0.170$ ,  $0.085$  and  $0.045$ , respectively. The geometric factor for  $u = 11/90$  is shown on the right.

### 3.2. The short oscillation length $L_{23}$ .

The value  $L_{23}$  can also be deduced from the oscillometry curves. This value can be compared with the neutrino energy which is usually well known, or can be measured independently very precisely [14]. For  $^{51}\text{Cr}$  the neutrino energy is presently known with the precision of 0.05 %. Since Eq. (3) is valid, if the value of global analysis for  $\Delta m_{23}^2 = 2.5 \times 10^{-3} (\text{eV})^2$  is used, this comparison will be helpful for assessment of the global analysis itself.

### 3.3. Neutrino mass hierarchy.

As the oscillometry method provides precise determination of  $\theta_{13}$  free of 8-fold degeneracy, the long baseline measurements in the same detector (LENA) with -neutrino beam would yield the information on the neutrino mass hierarchy without the need to change neither the energy of the neutrino beam nor the detector position. In this case the CERN- Pyhasälmä combination [15] looks quite promising for such type of measurements. Since short and long baseline experiments are disentangled by the energy region, both  $\theta_{13}$  and the sign of  $\{\Delta m_{13}^2\}$  experiments can be implemented using the same detector – LENA in Pyhasälmä.

## 4. Conclusions

We have discussed the importance of neutrino oscillometry involving low energy monochromatic neutrinos. Ideally one would like to employ gaseous TPC detectors with an extremely low energy threshold of 0.1 keV and neutrino sources with energy less than 50 keV. At present, however, one may have to content with a compromise, i.e. employ liquid detectors and use neutrino sources with energy of a few hundreds of keV. To this end the LENA detector is exceptionally well suited to perform precise determination of neutrino oscillation parameters thanks to the

relatively low detection threshold ( $\sim 200$  keV) and considerable length ( $\sim 100$ m). The needed electron-capture source emitting high-intensity monoenergetic and low-energy neutrinos can be manufactured by neutron irradiation in the core of a reactor. The disappearance of electron neutrinos can be followed over the full length of the detector by registering neutrino-electron scattering events. The resulting oscillometric curve and the total number of the events will provide accurate determination of the mixing angle  $\theta_{13}$ . The main advantages of the gaseous TPC detectors are:

- The energy threshold can be very low.
- One can explore real low energy neutrinos.
- The geometry is simple. The only  $L$ -dependence of the event rate comes from the oscillation.

The disadvantage is that, for at present realistic neutrino sources, the event rate is small. Furthermore the solar neutrino background may be serious. It does not, however, depend on  $L$  and, if necessary, it can be measured.

The main advantages of neutrino oscillometry with LENA are summarized as follows:

- The short oscillation length  $L_{23}$  can be determined directly and the value of  $\theta_{13}$  very precisely, without being affected by the 8-folded degeneracy.
- The mass hierarchy can be measured simultaneously with the same detector by performing a long baseline experiment (preferably CERN-Pyhasälmi) and using the determined  $\theta_{13}$ .
- The background from the solar neutrino events (whose total number is by a factor of two less than the expected effect) can be directly measured (by removing the source) and systematic uncertainty can be determined from the measurements with a different source of Table 1.

The disadvantage is that some spurious  $L$ -dependence of the event rate comes from the geometry. This, however, can be taken care of by the geometric factor  $g_{av}$ .

Acknowledgments: JDV is indebted to Prof. Jose Valle, the PASCOS10 organizing committee and Dr M. Gomez for their hospitality during PASCOS10, while Yu. N. N. to T. Enqvist, A. Erykalov, F.v. Feilitzsch, J. Hissa, K. Loo, J. Maalampi, D. Nesterenko, L. Oberauer, F. Thurne, W. Trzaska and M. Wurm for useful discussions and private communications.

## 5. References

- [1] Y. Fukuda *et al*, The Super-Kamiokande Collaboration, *Phys. Rev. Lett.* **86**, (2001) 5651; *ibid* **81** (1998) 1562 & 1158; *ibid* **82** (1999) 1810 ;*ibid* **85** (2000) 3999.
- [2] Q.R. Ahmad *et al*, The SNO Collaboration, *Phys. Rev. Lett.* **89** (2002) 011302; *ibid* **89** (2002) 011301; *ibid* **87** (2001) 071301.  
K. Lande *et al*, Homestake Collaboration, *Astrophys. J* **496**, (1998) 505  
W. Hampel *et al*, The Gallex Collaboration, *Phys. Lett. B* **447**, (1999) 127;  
J.N. Abdurashitov *et al*, Sage Collaboration, *Phys. Rev. C* **80** (1999) 056801;  
G.L Fogli *et al*, *Phys. Rev. D* **66** (2002) 053010.
- [3] K. Eguchi *et al*, The KamLAND Collaboration, *Phys. Rev. Lett.* **90** (2003) 021802, hep-exp/0212021.
- [4] Bahcall J N, Gonzalez-Garcia M and Peña-Garay C 2003 *JHEP* **0302** 009 (hep-ph/0212147)
- [5] Barger V and Marfatia D 2002 *Phys. Lett. B* **555** 144 (arXiv:hep-ph/0212126)
- [6] Vergados J and Novikov Y 2010 *Nucl. Phys. B* **839** 1 ; [arXiv:1006.3862, hep-ph]
- [7] Giomataris Y and Vergados J 2004 *Nucl. Instr. Meth. A* **530** 330
- [8] Giomataris Y *et al.* 1996 *Nucl. Instr. and Meth. A* **376** 29
- [9] Oberauer L, von Feilitzsch F and Potzel W 2005 *Nucl. Phys. B* **138** 108
- [10] E. Bougamont<sup>1</sup>, P. Colas<sup>1</sup>, J. Derre<sup>1</sup>, I. Giomataris, G. Gerbier, M. Gros, P. Magnier, X.F. Navick, P. Salin, I. Savvidis, G. Tsileadakis and J. D. Vergados, Ultra low energy results and their impact to dark matter and low energy neutrino physics, (to be published)
- [11] Borexino C 2009 *Nucl. Instr. and Methods A* **600** 568
- [12] Hampel W and Others 1998 *Phys. Lett. B* **420**
- [13] V Barger D Marfatia K W 2002 *Phys. Rev. D* **66** 053007 ; arXiv:hep-ph/0206038
- [14] Blaum K, Novikov Y and Werth G 2010 *Contemp. Phys.* **51** 149 [arXiv:0909.1095](physics.atom-ph)
- [15] Peltoniemi J and Sarkamo J 2006 *Nucl. Phys. B (Proc. Suppl.)* **155** 201

$^{51}\text{Cr}$  ( $t_{\text{meas}}=5\cdot 55\text{days}$ )

